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Aerobic Miniature Microbial Fuel Cells

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Introduction: Distributed autonomous sensor (DAS) networks will require sustainable energy-scavenging power sources for persistent surveillance applications. Ideally, these power sources will scale with the sensor size (micro/nanoelectromechanical) to enable covert deployment and a small power budget. Based on their ability to sustain power production for years while scavenging energy from a variety of environments and nutrients, microbial fuel cells (MFCs) are a viable solution to power water-borne DAS networks. However, to date, nearly all MFCs are large and bulky (100 cm^3 to m^3), making them significantly larger than many sensors and communication packages. Researchers in the NRL Chemistry and Oceanography Divisions have recently developed the first high power density miniature MFC (mini-MFC). The mini-MFC has a 2.0 cm^2 cross-section and a 1.2 cm^3 volume, making it orders of magnitude smaller than traditional MFCs. Additionally, the mini-MFC is designed to maximize current collection and proton diffusion to the cathode, enabling unprecedented power per area (3 W/m^2) and volume (500 W/m^3) when using graphite felt electrodes and *Shewanella oneidensis* cultured under micro-aerophilic conditions. These power densities are sustained when *S. oneidensis* biofilms on the anode are used with acellular media. Previous to this work, mixed consortia of bacteria with the ability to utilize electron donors efficiently needed to be used to produce current densities above 50 W/m^3. The mini-MFC design and size create a unique device that enhances power production per volume when compared to any other MFC design in the literature. These results are an indication that further size reductions may further increase power density and enable microbial energy scavengers to power DAS networks for Navy-relevant applications in the littoral water column.

Design of the Mini-MFC: Because of the relatively small power densities achieved by traditional macroscopic MFCs (1–100 W/m^3), it was surprising to find, when we began our work in FY2005, that the highest surface area to chamber volume ratio for any reported MFC was only 50 cm^{-1}. Higher surface area, in the form of roughened, granular, and/or fibrous surfaces, nearly always yields increased power output for all types of fuel cells. Traditional MFCs often use blocks of graphite with actual surface area equal to the geometric (footprint) surface area. By contrast, the mini-MFC (Fig. 1) is constructed using three-dimensional porous woven graphite felt electrodes to fill the entire anode and cathode chambers of the mini-MFC, enabling almost 600 cm^2 of exposed surface area to be presented in a chamber with a 2 cm^2 cross-section and 1.2 cm^3 volume (area-to-volume = 500 cm^{-1}). Additionally, instead of separating the anode and cathode by several centimeters through a narrow tube, the mini-MFC minimizes the distance between the two electrodes by placing them in contact with a 175 μm thick Nafion membrane that separates the two chambers. By decreasing the distance between the electrodes, proton diffusion between the chambers is maximized and the internal resistance is minimized.

Mini-MFC Accomplishments: As shown in Fig. 2, the mini-MFC generates the highest power per volume when using the three most popular cathode reactions: (a) oxygen reduction catalyzed by bare graphite, (b) reduction of ferricyanide, and (c) oxygen reduction catalyzed by Pt-modified graphite. These results were all obtained by using a pure culture of *S. oneidensis*, a bacterium known for its low energy conversion efficiency. All non-NRL results displayed in Fig. 2 utilize either a more energy efficient organism (in the bare carbon example) or mixed consortia of bacteria (ferricyanide and Pt cathode examples) that can more completely oxidize electron donors and nutrients avail-

FIGURE 1
NRL's mini-MFC (anode chamber shown).

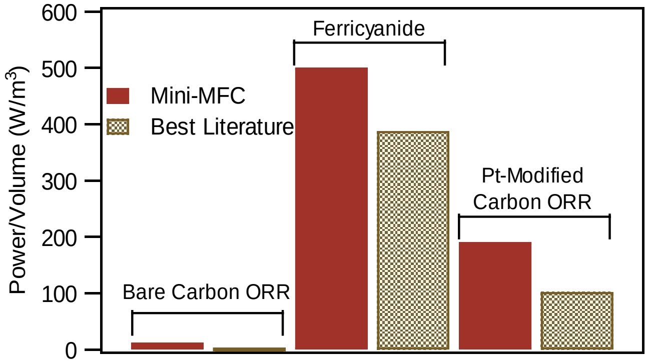

FIGURE 2
Power density per volume for the mini-MFC compared to best literature values for three cathode reactions. ORR = oxygen reduction reaction.

able to the microbes. Additional results have also been published that confirm the mini-MFC as a unique test reactor. We have published the first report of microbial energy production in a purely aerobic environment (Fig. 3(a)) and demonstrated the ability to generate significant power from *Shewanella spp.* using more complex and environmentally available carbon sources (Fig. 3(b)). These results have significant impact for Navy missions, as we hope to deploy these MFCs in the littoral regions of the water column where oxygen is pervasive and nutrient sources are complex (seaweed and plankton derivatives).

The Future of Water Column MFCs: We are now set to begin experiments to transition the mini-MFC from the laboratory into the littoral environment where DAS networks could detect a range of hazards from chem/bio weapons to submarines and divers. There are many challenges to deploying such a power source, including high salt concentrations, fluctuating temperatures, and limited and intermittent nutrient supplies. We are facing these challenges by developing MFCs that use consortia of salt-tolerant microorganisms. By using a mixed culture, diverse nutrients can be utilized and more completely converted to electricity. Additionally, both cold- and heat-tolerant *Shewanella spp.* can be added to help maintain power production under stressful environmental conditions. We believe these devices could be field-tested within the next three years, enabling persistent surveillance networks to be powered through energy-harvesting microbes.

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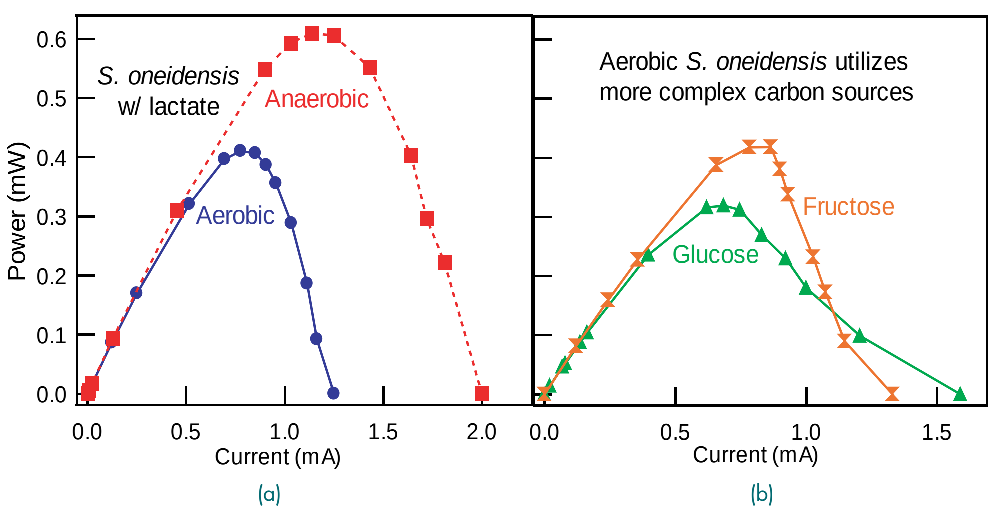

FIGURE 3
(a) Power versus current plot demonstrating for the first time that MFCs can generate power in completely aerobic environments. Power output dropped by roughly 30% due to oxygen scavenging of electrons in the anode chamber. (b) Power versus current plot demonstrating how *S. oneidensis* utilizes sugars to generate electricity under aerobic conditions.